The "Panghkawkwo graptolite bed" (Llandovery, Silurian), Myanmar and the location of the Sibumasu (or Sibuma) Terrane in the Silurian

David K. Loydell[a,*], Kyi Pyar Aung[b]

[a]School of Earth and Environmental Sciences, University of Portsmouth, Burnaby Road, Portsmouth PO1 3Q**L, UK**

[b]Department of Geology, Panglong University, Southern Shan State, Myanmar

ABSTRACT

The "Panghkawkwo graptolite bed" is shown to comprise several graptolitic horizons extending through the Aeronian (middle Llandovery) and into the lower Telychian (upper Llandovery). Graptolite assemblages are diverse indicating an outer shelf (or deeper) depositional environment. They are similar to those of Bohemia and Saudi Arabia (peri-Gondwanan Europe and core Gondwana respectively), but include also taxa (*Agetograptus* and species of *Metaclimacograptus*) not known from these regions, but which characterize lower latitude Llandovery graptolite assemblages. The evidence for the Silurian location of the Sibuma(su) Terrane is discussed. The presence of *Monograptus belophorus* and *Cyrtograptus rigidus* in the lower Sheinwoodian (Wenlock) of western Yunnan suggests a non-equatorial palaeolatitude. The Panghkawkwo graptolites suggest a location for Sibuma(su) between Gondwana and South China.

* Corresponding author. +44 2392842698

E-mail addresses: david.loydell@port.ac.uk (David K. Loydell), kyipyar73@gmail.com (Kyi Pyar Aung)

Keywords: Graptolite
Silurian
Palaeobiogeography
Llandovery
Sibumasu
Biostratigraphy

1. Introduction

Although much research has been undertaken, little has been published in recent years on the Silurian palaeontology of Myanmar. The purpose of this paper is to document the "Panghkawkwo graptolite bed" in the Southern Shan State, Myanmar, including its stratigraphical extent and the palaeobiogeographical affinities of its graptolite fauna. Eastern Myanmar was part of the Sibumasu (or Sibuma; Ridd 2016) Terrane during the Palaeozoic, the location of which in the Silurian has been the subject of considerable uncertainty and dispute. In addition to the new Panghkawkwo data, we consider also other published evidence for Sibuma(su)'s location, from Thailand, Malaysia and China.

2. Previous work

The first reference to the "Panghkawkwo graptolite bed" was by Reed (1932) where the locality is simply referred to as Panghkawkwo, near Loilem [it is approximately 3 km ESE of Loilem]. Elles, in Reed (1932, p. 210) identified seven species of graptolites which had been collected by J. Coggin Brown from the "bed" (*Glyptograptus serratus*, *Normalograptus scalaris*, "*Retiolites* sp.", *Stimulograptus sedgwickii*, *St. distans*, *Pristiograptus regularis* and *Campograptus lobiferus*: modern generic assignments have been used) from “a whitish shale” from Panghkawkwo and stated that they indicated the *Stimulograptus sedgwickii* Biozone. Both Gertrude Elles and F.R. Cowper Reed were based at the University of Cambridge, but the Sedgwick Museum’s small collection of graptolites from Myanmar contains material only from the Northern Shan State. Cocks and Fortey (2002, p. 58) noted that small collections of Myanmar fossils were donated by Reed to the Natural History Museum, London, but this too has no material from Panghkawkwo. Cocks and Fortey (2002, p. 57) stated that other fossil material from Myanmar published upon by Reed is “largely stored within the headquarters of the Geological Survey of India at Calcutta [Kolkata], who do not permit loan of the material.”

Brown and Sondhi (1933a) recorded the Panghkawkwo graptolite bed from both west and north of Loilem, describing (pp. 142–143), for example, exposures to the west of Loilem as “dark carbonaceous shale… containing abundant specimens of *Monograptus*, the species of which appear identical with those from the Panghkawkwo graptolite bed.” To the north, however, on the road to Wān Pong the age of the “bed” is stated (p. 144) as “believed to be not lower than Upper Valentian while it might be higher Salopian”. The term Valentian was introduced by Lapworth (in Armstrong et al., 1876) and is broadly equivalent to the Llandovery Series of modern usage. Definitions of the divisions of the Valentian changed over time (see Toghill, 1969), but the Upper Valentian as used in the early twentieth century is the equivalent of the Telychian Stage (upper Llandovery) as used today. The Salopian is a formerly used chronostratigraphical division broadly equivalent to the Wenlock and much of the Ludlow series. It may be that Pascoe (1959, see below) based his dating of the “Panghkawkwo graptolite bed” on Brown and Sondhi’s (1933a, p. 144) statement. However, the graptolites listed by Brown and Sondhi (1933a, p. 144) are as follows: “Provisional determinations by Miss G. L. Elles refer the specimens to *Climacograptus* sp. and *Monograptus sedgwickii* or *priodon*.” Presumably the Telychian or younger age is based upon the “or *priodon*” part of this statement. As shown below the “Panghkawkwo graptolite bed” does extend into the lower Telychian. It may, however, be that a younger stratigraphical horizon, not part of the “Panghkawkwo graptolite bed” occurs to the west of Loilem as Reed (1936, p. 108) recorded graptolites that “are mostly difficult to determine owing to their flattened-out condition”. They were identified as “*Monograptus* cf. *vulgaris* Wood”.

Brown and Sondhi (1933b) described “the graptolite beds of Mebyataung”, about 85 km ESE of Loilem. Three graptolitic horizons were recognised, referred to as Beds A–C. Gertrude Elles again identified the graptolites, which included *Campograptus millepeda* and *Stimulograptus sedgwickii* (modern generic assignments used) in Beds B and C, strongly suggesting that these beds correlate with the “Panghkawkwo graptolite bed”.

Reed (1936) added *Lituigraptus convolutus*, *Stimulograptus undulatus*, *Pristiograptus concinnus*, *Campograptus millepeda* and *Normalograptus* sp. (again modern generic assignments have been used) to the list of graptolites from Panghkawkwo and described the locality as follows: “Road cutting at Panghkawkwo, two miles south-east of Loilem.” He also listed localities to the west of Loilem, near Kyauktap and Chaunggauk with lists of graptolites including Aeronian species (*Demirastrites pectinatus*, recorded as “*Monograptus fimbriatus*”, and *Campograptus millepeda*), suggesting that strata equivalent to the “Panghkawkwo graptolite bed” are (or were) exposed at these localities also.

Whittington (1954) wrote up his “geological reconnaissance” of the Loilem area (mostly to the north of Loilem) made during six weeks in April–May 1941, commenting that all collections made were lost. He recorded “white and sandy micaceous shales containing poorly preserved monograptids” on the roadside between Loilem and Lai-Hka “at the 24th mile north of Loilem”, stating that these “appear to represent the Panghkawkwo graptolite bed”. A further graptolitic exposure, this time of pale purple mudstones (again assigned to the “Panghkawkwo graptolite bed”), was recorded a few hundred metres further north along the road; the overlying strata were described as “hard grey limestones”.

Pascoe (1959, p. 651), presumably based upon Reed (1932) and Brown and Sondhi (1933a), referred to “a richly fossiliferous band” at Panghkawkwo which includes two horizons: one from the "upper Valentian" and the other from the "higher Salopian" (see discussion above). He stated that the Panghkawkwo beds "are in places severely crushed" which may be a reference to the highly contorted layer also recorded herein. Pascoe (1959, p. 652) also noted that the graptolitic horizon was exposed to the north of Loilem on the western flank of Loi Samphu in Möng Pawn, where it yielded a similar assemblage to that recorded from Panghkawkwo, and about 19 km north of Möng Kung graptolitic shales were reported and stated to yield "*Monograptus* and *Diplograptus*".

Burton (1967, p. 36) highlighted Pascoe's (1959, p. 654) reference to a "zone containing *M. lobiferus*" occurring *above* the *sedgwickii* Biozone in the Southern Shan State. *Campograptus lobiferus* occurs stratigraphically below the *sedgwickii* Biozone (e.g. Štorch 1998a; Zalasiewicz et al. 2009). Presumably Pascoe's statement was based on Reed's (1936, p. 103) reference to "higher zones [than the *sedgwickii* Biozone]… containing *M. lobiferus*" having been discovered. It is possible that this apparent stratigraphical anomaly is the result of misidentification of a lower Telychian *Streptograptus* such as occurs in the highest graptolitic horizon of the Panghkawkwo section described herein (Fig. 2). Burton (1967, pp. 35–36) also listed all of the Llandovery graptolite species previously recorded from the Southern Shan State and stated that the *sedgwickii* Biozone "apparently occurs" at Panghkawkwo.

Using Elles, in Reed's (1932) faunal list, Berry and Boucot (1972) assigned the "Panghkawkwo Graptolite Bed" in the Loilem area to the upper Aeronian *Lituigraptus convolutus* and *Stimulograptus sedgwickii* biozones with the lower and upper boundaries of the bed marked as stratigraphically uncertain.

Thein (1973) commented little on the palaeontology of the Linwe Formation (which hosts the "Panghkawkwo graptolite bed"), mentioning only the abundant graptolites ("*Monograptus* and *Climacograptus*") and assigning the formation as a whole to the "Lower Silurian".

Garson et al. (1976) mapped an area in the Southern Shan State around Ye-ngan (about 75 km SSE of Mandalay) which included localities around Linwe (after which the Linwe Formation is named). They erected a Panghsa-pye Formation, varying in thickness from 15 m to 30 m, basing the name on the “Panghsa-pyé Graptolite Band” described in the Northern Shan State by La Touche (1913). Garson et al. (1976, p. 24) described the formation as consisting of “white to pale grey fissile shales and thinly laminated siltstones” which become sandier near the base and top of the formation and pass gradationally into underlying and overlying stratigraphical units. They also stated that “Fifty feet [c. 15 m] above its base the formation contains a highly fossiliferous band several tens of feet thick, with abundant well-preserved graptolites…” and that “Scattered graptolites occur throughout the formation.” Two small collections of graptolites are referred to: from Locality BA 482 (about 2.5 km N of Linwe) and AM 74 (about 300 m NW of Linwe). It is not indicated from what part of the formation they were collected or over what stratigraphical thickness. Both were assigned by them to the Aeronian. Garson et al.’s graptolite collections are housed at the Natural History Museum, London and have been examined by DKL. The collection from Locality BA 482 includes species recorded by us from Panghkawkwo: *Campograptus millepeda*, *Demirastrites similis* and *Normalograptus scalaris* (together with some specifically indeterminate fragments) and that from Locality AM 74 includes *Campograptus lobiferus* and *Rastrites approximatus*. These species co-occur in the middle Aeronian *Pribylograptus leptotheca* Biozone. Garson et al.’s (1976) graptolitic beds are therefore at least in part laterally equivalent to the “Panghkawkwo Graptolite Bed” (see Section 4. below). Whether the term Panghsa-pye Formation is appropriate will require examination of graptolites from the “Panghsa-pyé Graptolite Band” in the Northern Shan State and the establishment of the age of the lowermost graptolitic strata in the Linwe area. The graptolites listed by La Touche (1913, p. 126) from the vicinity of Panghsa-pyé were identified by Elles who suggested a Rhuddanian (probably *cyphus* Zone) age for them, which is older than the graptolitic strata sampled from Panghkawkwo. About 30 km NNE of Panghsa-pyé, however, at the village of Ngai-tao, La Touche (1913, p. 128) recorded *Rastrites peregrinus* indicating that graptolitic strata of Aeronian age do occur in the region.

Bender (1983) repeated Reed's (1932) list of graptolites from the "Panghkawkwo graptolite bed" and Berry and Boucot's (1972) biozonal assignment, but referred the bed to the Wabya Formation rather than the Linwe (or Panghsa-pye) Formation.

Wolfart et al. (1984) adopted a similar approach to Garson et al. (1976), referring to a Panghsa-pye Formation, with the "Panghkawkwo Graptolite Bed" being considered a synonym. Wolfart et al. (1984) summarize previous work on the graptolites from various localities throughout the Shan States.

Htwe (2011) recorded graptolite shales from the Linwe-Pegin area in the Pindaya Inlier in the western part of the Southern Shan State. This is part of the area mapped by Garson et al. (1976). In the "Pegin road cut section" two horizons of graptolitic shale are recorded, separated by "Limestone interbedded with argillaceous seam". Examination of photographs of graptolites from the Pindaya Inlier by DKL in 2009 indicates that at least one of the horizons is likely to be the lateral equivalent of the "Panghkawkwo graptolite bed".

Several other records of graptolites from the Southern Shan State occur in various unpublished theses and reports. Some of this unpublished work is summarized briefly in Aung (2012) in which both a Wabya Formation (table 2) and a "Wabya graptolite shale horizon" (table 8) are referred to in tables, but in the text only the Linwe Formation is mentioned. Several graptolites are listed and it is stated that within Myanmar as a whole six lower Silurian graptolite biozones are recognised ranging from the upper Rhuddanian *cyphus*/*lunata* Biozone through to the middle Telychian *griestoniensis* Biozone.

Despite the abundance of Llandovery graptolites at various localities in the Southern (and Northern) Shan States and the many records of them, both published and unpublished, with the exception of six small images of specimens (lacking locality and horizon information) described as "*graptolite* spp." by Aung (2012, fig. 6) none has ever been illustrated.

3. Locality information, lithologies and geological setting

The exposure studied is at 20°54’50.2”N, 97°35’35.2”, near Panghkawkwo village in the eastern Highland area, about 10 km southeast of Panglong, in the central part of the Southern Shan State. It is on the inside (north side) of a sharp bend in the Loilem to Namsam road (Fig. 1). Loilem is about 100 km SE of Mandalay. The logged section (Figs 1, 2) comprises 13.13 m of strata. Below this, a stratigraphically lower part of the original section was destroyed during road construction before it could be logged. The strata in the logged section are heavily weathered and comprise mostly shales and mudstones with a small number of siltstone and sandy shale beds, the latter forming the lowest beds exposed (Fig. 2). From 2.37 m to 2.61 m above the base of the section the strata are contorted. The intense weathering makes it very difficult to determine whether this disruption of the bedding is the result of penecontemporaneous soft sediment deformation or is of later tectonic origin. Micaceous shales and mudstones predominate in the ex situ material from lower stratigraphical levels.

Lithostratigraphically the strata belong to the middle part of the Linwe Formation, erected by Thein (1973), revised by Aung (2012) and named after Linwe village, Ye-ngan Township in the western part of the Southern Shan State. The formation conformably overlies the Nan-on Formation (Pindaya Group), stated to be of Late Ordovician age by both Thein (1973) and Aung (2012). The Linwe Formation comprises purple or grey calcareous shales with some argillaceous limestones in its lowermost part; the middle part includes, in addition to the lithologies exposed in the Panghkawkwo section described here, nodular limestones (the term “phacoidal” is widely used in descriptions of them); the upper part is characterized by light brown to grey, calcareous, micaceous, bioturbated shales, siltstones and marls interbedded with greenish grey argillaceous limestones (Aung 2012).

4. Graptolite biostratigraphy of the “Panghkawkwo graptolite bed”

In addition to the collections made from the logged section, many blocks of loose graptolitic material were amassed from stratigraphical horizons lower than those represented by the section that is still exposed, providing overall a collection of several hundred graptolites. In total, 97 graptolite species (including those in open nomenclature) have been identified from the ex situ and logged section collections. Most taxa are illustrated in Figures 3–10. Figured specimens are housed at the British Geological Survey, Keyworth. Biserial genera, with the exception of *Petalolithus* and retiolitids (one indeterminate retiolitid fragment was recorded), are common, with *Metaclimacograptus* and *Glyptograptus* exhibiting high diversity. Of the uniserial genera, *Pernerograptus*, *Demirastrites* and *Campograptus* are common whereas specimens of *Rastrites* and *Pribylograptus* are very rare.

4.1. Ex situ material (lower Aeronian)

The ex situ material includes a high diversity of graptolites (60 species) including 15 left in open nomenclature) from the lower part of the Aeronian Stage. The species present are listed in Table 1 and illustrated in Figures 5–10. Species indicating the lowermost Aeronian *triangulatus* Biozone include the index taxon; the presence of *Pseudorthograptus obuti* (Fig. 7L) demonstrates that the lower part of the biozone is represented. Although some species (e.g. *Normalograptus rectangularis* (Fig. 6C), *Ps. obuti*, *Rhaphidograptus toernquisti* (Fig. 9J)) present in the ex situ collections are known also from the Rhuddanian, there is no unequivocal evidence for Rhuddanian strata in the form of species known only from this stage, e.g. *Ps. mutablilis*, *Coronograptus cyphus*, *Dimorphograptus confertus*, *Pernerograptus revolutus*, *Cystograptus*, etc. are not present. An exception might appear to be *Neodiplograptus elongatus* (Churkin and Carter, 1970) described originally from the upper Rhuddanian of Alaska and subsequently from the middle Rhuddanian of Bohemia (Štorch, 1983) and Poland (Masiak et al., 2003). (The specimens assigned to this species from the upper Rhuddanian of Scotland by Rushton (in Stone, 1995) appear to increase in width more rapidly than *Ne. elongatus* and are considered here not to be this species). Melchin (1989), however, recorded the species from the lower Aeronian of the Canadian Arctic islands and the illustrated Panghkawkwo specimen (Fig. 6I) is on a slab with *Torquigraptus denticulatus* (Törnquist), suggesting that it is from *convolutus* Biozone, thus further extending the overall stratigraphical range of this species. It is of course possible that graptolitic strata within the "Panghkawkwo graptolite bed" do extend into the Rhuddanian, and that the ex situ blocks did not come from the lowest stratigraphical levels within the "bed".

Between the widely recognised *triangulatus* and *leptotheca* biozones various graptolite biozones have been identified (Loydell 2012). For example in Great Britain the *triangulatus* Biozone is succeeded by the *Neodiplograptus magnus* Biozone whereas in Bohemia a combined *triangulatus-pectinatus* Biozone is succeeded by a *Demirastrites simulans* Biozone. Recently, Williams et al. (2016) recognised a *Neodiplograptus thuringiacus* Biozone at a comparable stratigraphical level in the subsurface of Saudi Arabia. The Panghkawkwo collections include both *Ne. magnus* (Fig. 6J, 7N) and *Ne. thuringiacus* (Fig. 6H), but no specimens of *D. simulans* were encountered.

Taxa in the ex situ Panghkawkwo material indicative of the *leptotheca* Biozone include *Petalolithus folium* (Fig. 8D), *Lituigraptus richteri* (Fig. 8I), *Neolagarograptus helenae* (Fig. 9C) and *Campograptus millepeda* (Fig. 9I), all of which are stratigraphically restricted to this biozone (Štorch, 1998a). *Pribylograptus leptotheca* is not present in the ex situ material; indeed it is very rare overall, occurring (Fig. 4H) in only one collection from the upper *convolutus* Biozone. *Lituigraptus convolutus* is the stratigraphically youngest taxon present in the ex situ material. No *Cephalograptus extrema* (common within the logged section) were encountered, suggesting that only the lower part of the *convolutus* Biozone was destroyed by the road building activities.

4.2 Graptolite biostratigraphy of the logged section

Figure 2 shows the occurrences of graptolites within the logged part of the section which commences in the upper *Lituigraptus convolutus* Biozone. Graptolites from the logged section are illustrated in Figures 3–5. The lowest assemblage includes co-occurring taxa characteristic of this level, e.g. *Campograptus clingani* (Fig. 5B), "*Monograptus*" *limatulus* (Fig. 4F), *Torquigraptus*? *decipiens* (Fig. 4J) and *Cephalograptus extrema* (Fig. 3A). *C. clingani* is restricted to the *convolutus* Biozone whilst *Ce. extrema* first appears in the upper part of the biozone (Bjerreskov, 1975; Štorch, 1998a; Zalasiewicz et al., 2009). Assemblages characteristic of the upper *convolutus* Biozone continue for 2.37 m. Above this, to 2.61 m the strata are contorted. The index species (Fig. 5K) of the uppermost Aeronian *Stimulograptus halli* Biozone occurs immediately above the contorted strata. There is thus no evidence for the *St. sedgwickii* Biozone in the section. The *halli* Biozone continues to 6.59 m, above which there are fewer graptolitic horizons and these contain only sparse assemblages. The lowermost Telychian *guerichi* Biozone is indicated in the lower two of these higher graptolitic beds; the highest graptolitic horizon contains strongly ventrally curved and almost straight specimens of *Streptograptus* such as are common through much of the Telychian, but these are not identifiable to species level.

Overall the graptolitic strata at Panghkawkwo encompass the entirety of the Aeronian (with a possible break in the *sedgwickii* Biozone) and part of the Telychian. There are clearly several fossiliferous horizons, in some cases separated by apparently unfossiliferous beds and thus the term "graptolite bed" is something of a misnomer.

5. Palaeocontinental reconstructions, palaeoenvironment and palaeobiogeography

Within this section we discuss the evidence for the published palaeocontinental reconstructions for the Silurian, the pertinent published palaeobiogeographical data based largely on benthic shelly fossils (but with one very important graptolite record), and then consider the affinities of the Panghkawkwo graptolite fauna.

5.1. Sibumasu or Sibuma and its palaeolatitude

The Shan States of Myanmar have long been considered to form part of the Sibumasu Terrane (erected by Metcalfe, 1984) which included also what is now western Yunnan, western and most of peninsular Thailand, western Malaysia and north-eastern Sumatra, today approximately 4000 km overall in length. Torsvik and Cocks (2013a) noted that Sibumasu has been much "distorted, both by Early Mesozoic tectonism and also by the intrusion of very substantial Triassic granites… and was probably both larger and of a different shape" than shown on their (and presumably other) palaeogeographical maps.

Recently, Ridd (2016) proposed bisection of the Sibumasu Terrane into two discrete Gondwana-derived blocks: the Irrawaddy Block (to the west and including also north-eastern Sumatra) and the Sibuma Block, with the Shan States forming part of the latter, bounded to the west by the Median Myanmar Suture Zone of Mitchell et al. (2015).

A significant challenge in determining the palaeogeographical location of Sibumasu has been the paucity/lack of reliable palaeomagnetic data and hence comparisons of fossil assemblages from different continents/terranes have provided important evidence. To quote Metcalfe (2005, p. 172): "reconstructions based purely on palaeomagnetic data [are] difficult and suspect."

Several reconstructions show Sibumasu at equatorial latitudes or just to the north of the equator during the Ordovician and Silurian (e.g. Metcalfe, 2005; Torsvik and Cocks, 2009, 2013a, 2013b, 2016; Cocks and Torsvik, 2013). Exceptions are the reconstructions of Rong et al. (2003) who show Sibumasu straddling the 30°S line of latitude in the Silurian and of Agematsu et al. (2008, fig. 963) who show Sibumasu between 30° and 45° S in the Late Ordovician.

With regard to palaeolatitude (and the overall location of Sibumasu) graptolite records from the upper Sheinwoodian (lower Wenlock Series) of western Yunnan, China are very significant. The biozonal index species *Monograptus belophorus* (= *M. flexilis*) and *Cyrtograptus rigidus* have both been recorded (Ni and Lin, 2000; Zhang et al., 2014). These occurrences are very interesting biogeographically because the late Sheinwoodian was a period of marked provincialism of graptolite faunas. Both species are well known from Avalonia, Baltica and peri-Gondwanan Europe, but have not been recorded from Arctic Canada despite intensive study of graptolites from this region (Lenz et al., 2012). Melchin (1989) had recognised graptolite provincialism earlier in the Silurian, with faunal similarities between localities straddling the late Llandovery equator: Arctic Canada (marginal Laurentia), Siberia, Kazakhstan, South China, North China and the Uralian margin of Baltica. The upper Sheinwoodian graptolite record from western Yunnan offers support for a non-equatorial location for Sibumasu during the Silurian.

The orientation of Sibumasu has varied in recent reconstructions: Torsvik and Cocks (2009, fig. 5) show the Yunnan and Shan States end of Sibumasu to the north (at about 15–20° N during the mid Silurian) with the Malay Peninsula end occupying an equatorial position. A similar orientation is shown on the maps used by Goldman et al. (2011) and Zhang et al. (2014). This orientation is reversed on Rong et al.'s (2003), Metcalfe's (2005), Agematsu et al.'s (2008), Cocks and Torsvik's (2013) and Torsvik and Cocks' (2016) reconstructions.

Much has been published on the palaeobiogeographical affinities of Ordovician shelly fossils (particularly trilobites and brachiopods) from Sibumasu (Fang, 1994; Cocks and Zhan, 1998; Cocks and Fortey, 1997, 2002; Fortey and Cocks, 1998; Cocks et al., 2005, Zhou and Zhen, 2008); significantly less (Fang, 1994) on the Silurian.

Below we consider the evidence for Sibumasu's location in relation to South China and then in relation to the north-western Australian margin of Gondwana.

5.2. Proximity to South China

Cocks and Torsvik (2002) located Sibumasu close to South China in the Silurian on the basis of “strong faunal similarity at various times”; proximity is maintained on their later (Torsvik and Cocks, 2009, 2013a, 2013b, 2016; Cocks and Torsvik, 2013) maps and on that of Metcalfe (2011).

Cocks and Zhan (1998) studied the Upper Ordovician brachiopods of the Shan States and noted that some genera (e.g. *Saucrorthis*) are known only from here and from South China and stated: “This confirms that the South China and Sibumasu terranes were not far apart”. Similarly, Fortey and Cocks (1998, p. 51) stated that Middle and Upper Ordovician trilobite faunas from Sibumasu are “strikingly similar” to those of South China.

What Fortey and Cocks (1998, pp. 51, 54) emphasize is that there is a difference between the biogeographical signals of the “earlier and later Ordovician” resulting in the paradox of Sibumasu apparently switching between proximity to North China with a location adjacent to Australia in the early Ordovician and a close relationship with South China in the late Ordovician. Their possible solutions included (1) movement of Sibumasu away from North China/Australia towards South China during the Silurian, and (2) the suggestion that the differences between North and South China nautiloid faunas had been overemphasized by previous workers. They concluded that they favoured “a close biogeographical and physical proximity of South China and Sibumasu”. Agematsu et al. (2008, fig. 7) show movement of Sibumasu away from Australia during the Late Ordovician, but show it maintaining a similar proximity to South China.

Zhou and Zhen (2008) noted that the mid–late Darriwilian (Middle Ordovician) trilobites of the Baoshan area, western Yunnan seem to be a “mixture… exhibiting two different biogeographical affinities”, some taxa being typical of North China, others of South China.

Zhang et al. (2009) studied Darriwilian (Middle Ordovician) graptolites from western Yunnan and concluded that the “graptolite fauna shows a considerable similarity to those contemporary in Baltica and the Yangtze Region of South China.”

Fang (1994) and Rong et al. (2003, p. 287) noted, however, that uppermost Silurian–Devonian scyphocrinoids, which have been found at various locations on Sibumasu, are recorded also from Europe, North Africa and North America, but not South China (or Australia). Rong et al. (2003, p. 288) also summarized various Devonian faunal occurrences from Sibumasu, none of which shows affinities with South China.

Rong et al. (2003, p. 290) stated that there was "a remarkable… change to faunal provincialism in Sibumasu in the Late Ordovician and Early Silurian" and that "barriers to faunal exchange between Sibumasu and South China must have developed." They proposed "that Sibumasu was located between southern Europe and South China".

The balance of published evidence therefore seems to favour Sibumasu and South China being in close proximity through much of the Ordovician after which, through the mid Palaeozoic, they became increasingly distant from each other.

5.3. Attachment to Gondwana

Heralding a return to the palaeocontinental reconstruction of the region by Burrett et al. (1990), Torsvik and Cocks (2013b, p. 5) stated that Sibumasu is "now considered an integral part of Gondwana", abandoning their previous (Cocks and Torsvik 2002) proposal that Sibumasu formed a separate continent several thousand kilometres from the northern margin of Gondwana and separated from it by Annamia and intervening oceans to north and south. Metcalfe (2005) similarly included Sibumasu as "part of Indian-Australian 'Greater Gondwana'" and placed it in the Silurian (fig. 13b) in close proximity to north-western Australia. Ridd (2016) concluded, however, that the "Sibuma block is thought to have been further outboard from Gondwana". How much further is not stated and no palaeogeographical reconstruction is presented for the Silurian.

Cocks et al. (2005) had previously concluded, based on palaeomagnetic data from South China and the similarity of Sibumasu faunas to those of South China that unless the palaeomagnetic data for South China and/or Gondwana were "misleading", Sibumasu was "at some distance from Gondwana". Fang (1994) had suggested that Sibumasu had rifted away from Gondwana in the mid

Ordovician. Prior to this, Sibumasu faunas showed strong affinities with those of Australia, but in the Silurian and Devonian “Rhenish–Bohemian elements dominated in the Sibumasu faunas.” This is in agreement with the observations of Burrett and Stait (1985) who commented on the considerable similarity of the upper Cambrian trilobite and Ordovician nautiloid, gastropod, polyplacophoran, rostroconch, brachiopod, conodont and stromatoporoid faunas of Australia and Sibumasu.

In combination with the Cambrian and Ordovician faunal data, one of the main lines of evidence cited for Sibumasu being attached to Gondwana through much of the Palaeozoic, most probably along its north-western Australian margin, is glacial-marine diamictites and cool water faunas, mostly of early Permian age “distributed along the entire length of Sibumasu” (Metcalfe, 2005, p. 174). Ridd (2016), however, notes that to the east of the Median Myanmar Suture Zone (i.e. on Sibuma), there are only “local, thin, Lower Permian diamictite units” which have been interpreted as “ice-rafted deposits, laid down at a greater distance from the Gondwana margin” than the diamictite-bearing, marine mass-flow deposits of the Irawaddy Block.

Rong et al. (2003, p. 290) concluded that “Cambrian and earlier Ordovician biotas of Sibumasu have strong Australian affinities” and this was Metcalfe’s (2005) view also. However, as noted above with regard to South China, Rong et al. (2003) noted that there was “a remarkable later change to faunal provincialism in Sibumasu in the Late Ordovician and Early Silurian” and (p. 287) commented on the occurrence of uppermost Silurian and Devonian brachiopod species in western Yunnan that occur in “Podolia, Bohemia, and elsewhere in Europe” and noted also (as had Fang, 1994) that scyphocrinoids, which have been found at various locations on Sibumasu, are recorded also from Europe, North Africa and North America, but not Australia (or South China). Similarly, Fortey (1989) had described an Early Devonian trilobite assemblage from southern Thailand “with close specific comparisons with Turkey, Morocco and Bohemia.” As noted above, Rong et al. (2003) concluded “that Sibumasu was located between southern Europe and South China” but not adjacent to Australia.

The shallow marine (BA2–3) late Silurian *Retziella* Fauna (Rong et al., 1995) is known from Australia and several East and South-East Asian continental blocks forming what has been termed a Sino-Australian Province. The *Retziella* Fauna has not been recorded from Sibumasu, however (Metcalfe, 2005, fig. 7; Cocks and Torsvik, 2013, fig. 12).

Unfortunately, there are no exposed Silurian strata in north-western Australia (i.e. along the Gondwanan margin to which Sibumasu is usually portrayed as attached): all data inevitably come from the subsurface (Canning and Carnarvon basins, Western Australia; Amadeus Basin, Northern Territory, Bonaparte and the offshore Bonaparte Basin). Some of the Silurian sediments were laid down under terrestrial conditions, some others are evaporites and there have been few palaeontological studies (see summary in Talent et al., 2003). The available data are insufficient for palaeobiogeographical comparisons for the Silurian. For the Middle Devonian, however, Burrett et al. (1990) highlighted the similarity of turiniform thelodont species from Australia, western Yunnan and northern Thailand and conodonts of the polygnathid *Polygnathus labiosus* lineage from Australia and Thailand.

Overall the published palaebiogeographical evidence suggests close proximity of Sibumasu and Australia in the Cambrian and through much of the Ordovician. Silurian faunas show significant differences whilst there is clearly conflicting evidence from the Devonian.

5.3. Environmental and palaeobiogeographical significance of the Panghkawkwo graptolites

5.3.1. Environmental setting

Irrespective of the underlying causes, planktic Silurian graptolites show a distinctive diversity pattern in relation to proximity to land and/or water depth. They are generally absent from inner shelf settings, occur in low diversity assemblages mid shelf, and show increased diversity on the outer shelf and in basinal/oceanic environments (e.g. Štorch, 1998b; Williams et al., 2016).

The Panghkawkwo assemblages are of high diversity with individual bedding surfaces often bearing several genera and species. The graptolite diversity therefore is more in agreement with Cocks and Torsvik's (2013) palaeogeographical reconstruction that shows the Shan States occupying a deep shelf to oceanic position during both the Rhuddanian (early Llandovery) and late Ludlow than with those of Torsvik and Cocks (2009) and Metcalfe (2011) who show the same area as being land or shallow shelf during the mid Silurian or mid-late Silurian respectively.

5.3.2. Palaeobiogeography

With any comparison of fossil assemblages one is inevitably limited by the extent of published records. Aeronian (middle Llandovery) graptolite faunas are well documented, for example, from Great Britain (summarized in Zalasiewicz et al., 2009), Bohemia (e.g. Štorch, 1998a) and Saudi Arabia (Williams et al. 2016), but there are very few publications on Llandovery graptolites from Australia. Rickards and Sandford (1998) recorded ten (but illustrated only one) confidently identified Aeronian species (and listed others under open nomenclature) from central Victoria, but overall the Australian Aeronian graptolite record is currently insufficient to make meaningful comparisons. Numerous publications describe Aeronian graptolites from South China, e.g. Chen and Lin (1978), Ni (1978), Chen (1984) and Fu and Song (1986).

The location of Perunica (which includes Bohemia) in the Silurian is debated (see discussion in Torsvik and Cocks, 2013b), but is usually referred to as part of peri-Gondwanan Europe. Arabia, on the other hand, is part of what Torsvik and Cocks (2013a) refer to as “core Gondwana”. According to all recent published palaeogeographical maps it is the closest Gondwanan region with a good Aeronian graptolite record to Sibumasu and for that reason its graptolite fauna (which is very similar to that from Bohemia) will be compared first with that from Panghkawkwo.

More than half of the graptolites identified to species level from Panghkawkwo were recorded also by Williams et al. (2016) from Saudi Arabia. Those Panghkawkwo graptolites not recorded from Saudi Arabia include several species within the *Pernerograptus austerus* group which often require a considerable length of rhabdosome to be preserved in order to identify them confidently; this is not always available in core material. More conspicuously absent from Saudi Arabia (and also from Bohemian graptolite assemblages) are the genus *Agetograptus* and two species of *Metaclimacograptus*. These will be discussed below.

Agetograptus Obut and Sobolevskaya (in Obut et al., 1968), which is well-represented in the Pangkawkwo ex situ material (Figs 7D, 8B, 8F), was originally described from Siberia and has been subsequently recorded from China (NIGP, 1974, pl. 98, fig. 2), Sweden (Loydell, 1991), Arctic Canada (Melchin, 1989, 1998) and Kazakhstan (Koren' and Rickards, 1996). The genus has never been recorded from Gondwana or peri-Gondwanan terranes; it was one of the taxa that Melchin (1989) recognised as being restricted to low latitudes in the Llandovery. One of the *Agetograptus* species present at Panghkawkwo, *Ag. malayensis* (Jones, 1973)(Fig. 7D), was first described from another Sibumasu locality (Pulau Langgun, Langkawi Islands, Malaysia); it occurs also in South China where it was described as *Bulmanograptus anhuiensis* by Li (1987). *Metaclimacograptus hubeiensis* (NIGP, 1974)(Fig. 7E) has been recorded previously only from the South China Plate. *Metaclimacograptus sculptus* (Chen and Lin, 1978), also present at Panghkawkwo (Fig. 3I), was first described from South China, and subsequently has been found in Arctic Canada (Melchin, 1989; note that the specimen illustrated by Melchin (1998, pl. 2, fig. 8) appears not to be this species, however) and Kazakhstan (as its junior synonym *Me. khvorovi* Koren' and Rickards, 1996).

The Panghkawkwo graptolite fauna therefore is similar to that of Saudi Arabia and peri-Gondwanan Europe but also includes taxa that are not recorded from these regions and that indicate some affinities with South China and other lower latitude areas.

5.3.3. Similarities and differences within Sibumasu faunal assemblages

Even within the Sibumasu (or Sibuma) Terrane, contemporaneous shelly fossil assemblages can be markedly dissimilar. For example, Cocks and Fortey (2002) described the brachiopods and trilobites of the Panghsa-Pye Formation in the Northern Shan State which they dated as latest

Ordovician. However, they noted some "surprising differences" between this Panghsa-Pye fauna and that of the uppermost Ordovician of southern Thailand described by Cocks and Fortey (1997), with only one (widespread) species in common. The localities are, however, towards opposite ends of the 4000 km long terrane so perhaps some faunal differences might be expected.

With regard to Llandovery graptolites, there are few descriptions or illustrations from the Thai and Malaysian parts of Sibumasu. The graptolites considered to be of Llandovery age described by Kobayashi and Igo (1965) from northwest Thailand were subsequently shown to be Devonian (Jaeger et al. 1969). Agematsu et al. (2006) described low diversity assemblages from close to the Ordovician/Silurian boundary in the Satun area, southern peninsular Thailand. The species listed are geographically widespread.

The most important published account of Silurian graptolites from the Malaysian part of Sibumasu is that of Jones (1973), with the most significant section undoubtedly being that on Palau Langgun, Langkawi Islands, Malaysia. Jones (1973) assigned his beds 10–15 (a total thickness of 3.63 m) of the Palau Langgun section to the Aeronian. Only his new species are illustrated by Jones and his collections (housed in Ipoh, Malaysia) would benefit from restudy. What is conspicuous from the range chart, however, is the complete absence of the *Demirastrites* species (e.g. *D. triangulatus*, *D. pectinatus*) that are so characteristic of the lower Aeronian worldwide and are common in the Panghkawkwo collections (Figs 8G, 9E). Determining whether their absence is a reflection of a stratigraphical gap in the Palau Langgun section requires re-examination of Jones' graptolite collection and/or restudy of the section. Two of Jones' new species (*Ag. malayensis* (Fig. 7D) and *G. burtoni* (Fig. 7F)) have been found at Panghkawkwo.

Several papers have been published on the northern extension of Sibumasu into western Yunnan, China. Much of the information in these is summarized and supplemented by new data in Zhang et al. (2014). The most important section in the area is the Laojianshan section, Baoshan, about which Zhang et al. (2014, p. 94) stated: "the stratigraphy, palaeontology, sedimentology and palaeoenvironments have, surprisingly, been little studied." An apparently continuous sequence of graptolite biozones from the Hirnantian *Metabolograptus extraordinarius* Biozone through to the Aeronian *Lituigraptus convolutus* is shown by Zhang et al. (2014, fig. 5.34) in the black shales and cherts of the Jenhochiao Formation. Higher Llandovery levels in the Laojianshan section have been obscured by a landslide. However, Sung (1941) and Ni et al. (1982) indicated that graptolitic strata in western Yunnan extend into the Telychian, above which are the limestones of the Lichaiba Formation.

Zhang et al. (2014, fig. 5.45) illustrated a few mid Aeronian graptolites from the Laojianshan section: *Metaclimacograptus sculptus*, *Lituigraptus convolutus*, *Campograptus lobiferus*, *C. millepeda* (fig. 5.45G, identified by Zhang et al. as *C. lobiferus*) and *Cephalograptus cometa*. All but the last of these (which is rarely common; see e.g. Štorch, 1998a, two specimens in a collection of c. 10,000 graptolites) occur in the Panghkawkwo collections.

Clearly more research is needed on Llandovery graptolites from Sibumasu.

Conclusions

The stratigraphical extent of the “Panghkawkwo graptolite bed” is clearly far more extensive than indicated by published literature (e.g. Berry and Boucot, 1972) and rather than representing just part (two biozones) of the Aeronian encompasses all of this stage and part of the overlying Telychian. The Aeronian graptolite faunas studied are of high diversity, indicating an outer shelf environment or deeper, and show affinities with both (peri-)Gondwana and South China, suggesting that a locality between the two is reasonable.

Acknowledgements

We thank Claire Mellish and Adrian Rushton (Natural History Museum, London) for making the collections of graptolites from Myanmar housed there available for study. Matt Riley provided details of graptolites from Myanmar housed in the Sedgwick Museum, Cambridge. Mike Melchin is thanked for his helpful comments as referee.

References

Agematsu, S., Sashida, K., Ibrahim, A.B., 2008. Biostratigraphy and paleobiogeography of Middle and Late Ordovician conodonts from the Langkawi Islands, northwestern peninsular Malaysia. *Journal of Paleontology* 82, 957–973.

Agematsu, S., Sashida, K., Salyapongse, S., Sardsud, A., 2006. Ordovician-Silurian boundary graptolites of the Satun area, southern peninsular Thailand. Palaeontological Research 10, 207–214.

Armstrong, J., Young, J., Robertson, D., 1876. Catalogue of the western Scottish fossils. Blackie & Son, Glasgow. 164 pp.

Aung, A.K., 2012. The Paleozoic stratigraphy of Shan Plateau, Myanmar – an updated version. Journal of the Myanmar Geosciences Society 5(1, special volume), 1–73.

Bender, F., 1983. Geology of Burma. Gebrüder Borntraeger, Berlin, Stuttgart. viii+295 pp.

Berry, W.B.N., Boucot, A.J., 1972. Correlation of the Southeast Asian and near Eastern Silurian rocks. Special Paper of the Geological Society of America 137, 1–65.

Bjerreskov, M., 1975. Llandoverian and Wenlockian graptolites from Bornholm. Fossils and Strata 8, 1–94.

Brown, J.B., Sondhi, V.P., 1933a. Geological reconnaissance in the Southern Shan States. Records of the Geological Survey of India 67(2), 135–165.

Brown, J.B., Sondhi, V.P., 1933b. The geology of the country between Kalaw and Taunggyi, Southern Shan States. Records of the Geological Survey of India 67(2), 166–248.

Burrett, C., Long, J., Stait, B., 1990. Early–Middle Palaeozoic biogeography of Asian terranes derived from Gondwana. In: McKerrow, W.S., Scotese, C.R. (Eds.), Palaeozoic palaeogeography and biogeography. Geological Society, London, Memoir 12, 163–174.

Burrett, C., Stait, B., 1985. South-east Asia as part of an Ordovician Gondwanaland – a palaeogeographic test of a tectonic hypothesis. Earth and Planetary Science Letters 75, 184–190.

Burton, C.K., 1967. Graptolite and tentaculite correlations and palaeogeography of the Silurian and Devonian in the Yunnan-Malaya geosyncline. Transactions and Proceedings of the Palaeontological Society of Japan, New Series 65, 27–46.

Chen, X., 1984. Silurian graptolites from southern Shaanxi and northern Sichuan with special reference to classification of Monograptidae. Palaeontologia Sinica, New Series B 166(20), 1–102.

Chen, X., Lin, Y., 1978. Lower Silurian graptolites from Tongzi, northern Guizhou. Memoirs of Nanjing Institute of Geology and Palaeontology, Academia Sinica 12, 1–76.

Churkin, M., Carter, C., 1970. Early Silurian graptolites from southeastern Alaska and their correlation with graptolitic sequences in North America and the Arctic. Professional Paper of the Geological Society of America 653, 1–51.

Cocks, L.R.M., Fortey, R.A., 1997. A new *Hirnantia* fauna from Thailand and the biogeography of the latest Ordovician of South-East Asia. Geobios Mémoire Spécial 20, 117–126.

Cocks, L.R.M., Fortey, R.A., 2002. The palaeogeographical significance of the latest Ordovician fauna from the Panghsa-Pye Formation of Burma. Special Papers in Palaeontology 67, 57–76.

Cocks, L.R.M., Fortey, R.A., Lee, C.P., 2005. A review of Lower and Middle Palaeozoic biostratigraphy in west peninsular Malaysia and southern Thailand in its context within the Sibumasu Terrane. Journal of Asian Earth Sciences 24, 703–717.

Cocks, L.R.M., Torsvik, T.H., 2002. Earth geography from 500 to 400 million years ago: a faunal and palaeomagnetic review. Journal of the Geological Society 159, 631–644.

Cocks, L.R.M., Torsvik, T.H., 2013. The dynamic evolution of the Palaeozoic geography of eastern Asia. Earth-Science Reviews 117, 40–79.

Cocks, L.R.M., Zhan, R.-B., 1998. Caradoc brachiopods from the Shan States, Burma (Myanmar). Bulletin of the Natural History Museum London (Geology) 54(2), 109–130.

Fang, Z.-J., 1994. Biogeographic constraints on the rift–drift–accretion history of the Sibumasu block. Journal of Southeast Asian Earth Sciences 9, 375–385.

Fortey, R.A., 1989. An Early Devonian trilobite fauna from Thailand. Alcheringa 13, 257–267.

Fortey, R.A., Cocks, L.R.M., 1998. Biogeography and palaeogeography of the Sibumasu terrane in the Ordovician: a review. In: Hall, R., Holloway, J.D. (Eds.), Biogeography and geological evolution of SE Asia. Backhuys, Leiden, pp. 43–56.

Fu, L., Song, L., 1986. Stratigraphy and paleontology of Silurian in Ziyang Region (transitional belt). Bulletin of the Xi'an Institute of Geology and Mineral Resources, Chinese Academy of Geological Sciences 14, 1–198.

Garson, M.S., Amos, B.J., Mitchell, A.H.G., 1976. The geology of the area around Neyaungga and Ye-ngan, Southern Shan States, Burma. Overseas Memoir of the Institute of Geological Sciences 2, 1–70.

Goldman, D., Mitchell, C.E., Melchin, M.J., Fan, J., Wu, S.-Y., Sheets, H.D., 2011. Biogeography and mass extinction: extirpation and re-invasion of *Normalograptus* species (Graptolithina) in the Late Ordovician palaeotropics. Proceedings of the Yorkshire Geological Society 58, 227–246.

Htwe, Y.M., 2011. The development of the transgressive Silurian rocks of the Linwe-Pegin area, Shan State (South). Universities Research Journal 4(5), 33–43.

Jaeger, H., Stein, V., Wolfart, R., Stoppel, D., 1969. Fauna (Graptolithen, Brachiopoden) der unterdevonischen Schwarzschiefer Nord-Thailands. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen 133, 171–190.

Jones, C.R., 1973. The Siluro-Devonian graptolite faunas of the Malay Peninsula. Overseas Geology and Mineral Resources 44, 1–28.

Kobayashi, T., Igo., H., 1965. On the occurrence of graptolites shales in north Thailand. Japanese Journal of Geology and Geography 36, 37–44.

Koren', T.N., Rickards, R.B., 1996. Taxonomy and evolution of Llandovery biserial graptoloids from the southern Urals, western Kazakhstan. Special Papers in Palaeontology 54, 1–103.

La Touche, T.H.D., 1913. Geology of the Northern Shan States. Memoirs of the Geological Survey of India 39(2), 1–379.

Lenz, A.C., Senior, S., Kozłowska, A., Melchin, M.J., 2012. Graptolites from the mid Wenlock (Silurian), middle and upper Sheinwoodian, Arctic Canada. Palaeontographica Canadiana 32, 1–93.

Li, J.-J., 1987. On the origin of dimorphograptids. Bulletin of the Geological Society of Denmark 35, 171–177.

Loydell, D.K., 1991. Isolated graptolites from the Llandovery of Kallholen, Sweden. Palaeontology 34, 671–693.

Loydell, D.K., 2012. Graptolite biozone correlation charts. Geological Magazine 129, 124–132.

Loydell, D.K., Maletz, J., 2009. Isolated graptolites from the *Lituigraptus convolutus* Biozone (Silurian, Llandovery) of Dalarna, Sweden. Palaeontology 52, 273–296.

Masiak, M., Podhalańska, T., Stempień-Sałek, M., 2003. Ordovician-Silurian boundary in the Bardo Syncline, Holy Cross Mountians, Poland – new data on fossil assemblages and sedimentary succession. Geological Quarterly 47, 311–330.

Melchin, M.J., 1989. Llandovery graptolite biostratigraphy and palaeobiogeography, Cape Phillips Formation, Canadian Arctic Islands. Canadian Journal of Earth Sciences 26, 1726–1746.

Melchin, M.J., 1998. Morphology and phylogeny of some early Silurian 'diplograptid' genera from Cornwallis Island, Arctic Canada. Palaeontology 41, 263–315.

Metcalfe, I., 1984. Stratigraphy, palaeontology and palaeogeography of the Carboniferous of Southeast Asia. Mémoires de la Société Géologique de France 147, 107–118.

Metcalfe, I., 2005. Asia/South-East. In: Selley, R.C., Cocks, L.R.M., Plimer, I.R. (eds.), Encyclopaedia of Geology. Elsevier, Oxford, pp. 169–196.

Metcalfe, I., 2011. Palaeozoic-Mesozoic history of SE Asia. In: Hall, R., Cottam, M.A., Wilson, M.E.J. (eds.), The SE Asian gateway: history and tectonics of the Australia–collision. Geological Society, London, Special Publication 355, 7–35.

Mitchell, A.H.G., Htay, M.T., Htun, K.M., 2015. The medial Myanmar suture zone and the western Myanmar-Mogok foreland. Journal of the Myanmar Geosciences Society 6, 73–88.

Nanjing Institute of Geology and Palaeontology, Academia Sinica (NIGP) 1974. Handbook of stratigraphy and palaeontology of Southwest China. 454 pp.

Ni, Y.-N., 1978. Lower Silurian graptolites from Yichang, western Hubei. Acta Palaeontologica Sinica 17, 387–416.

Ni, Y.-N., Chen, T.-E., Cai, C.-Y., Li, G.-H., Duan, Y.-X., Wang, J.-D., 1982. The Silurian rocks in Western Yunnan. Acta Palaeontologica Sinica. 21, 119–132.

Ni, Y.-N., Lin, Y.-K., 2000. Wenlock graptolites from the Upper Jenhochiao Formation of Shidian, Western Yunnan, China. Acta Palaeontologica Sinica 39, 343–355.

Obut, A.M., Sobolevskaya, R.F., Merkureva, A.P., 1968. Graptoliti Llandoveri v kernach burovych skvazhin Norilskogo rayona. Akademiya Nauk SSR, Sibirskoje Otdelenie Institut Geologii i Geofiziki. Ministerstvo Geologii SSSR, Nauchno-Issledovatel'sky Institut Geologii Arktiki. 162 pp.

Pascoe, E.H., 1959. A manual of the geology of India and Burma. Volume 2. 3rd edition. Geological Survey of India, Calcutta. pp. 485–1343.

Reed, F.R.C., 1932. Notes on some Lower Palaeozoic fossils from the Southern Shan States. Records of the Geological Survey of India 66(2), 181–211.

Reed, F.R.C., 1936. The Lower Palaeozoic faunas of the Southern Shan States. Memoirs of the Geological Survey of India, New Series 21(3), 1–130.

Rickards, R.B., Sandford, A.C., 1998. Llandovery–Ludlow graptolites from central Victoria: new correlation perspectives of the major formations. Australian Journal of Earth Sciences 45, 743–763.

Ridd, M.F., 2016. Should Sibumasu be renamed Sibuma? The case for a discrete Gondwana-derived block embracing western Myanmar, upper peninsular Thailand and NE Sumatra. Journal of the Geological Society 173, 249–264.

Rong, J.-Y., Boucot, A., Su, Y.-Z., Strusz, D.L., 1995. Biogeographical analysis of late Silurian brachiopod faunas, chiefly from Asia and Australia. Lethaia 28, 39–60.

Rong, J.-Y., Chen, X., Su, Y.-Z., Ni, Y.-N., Zhan, R.-B., Chen, T.-E., Fu, L.-P., Li, R.-Y., Fan, J.-X. 2003. Silurian palaeogeography of China. New York State Museum Bulletin 493, 243–298.

Stone, P., 1995. Geology of the Rhins of Galloway district. Memoir for 1:50 000 geological sheets 1 and 3 (Scotland). HMSO, London. 102 pp.

Štorch, P., 1983. The genus *Diplograptus* (Graptolithina) from the lower Silurian of Bohemia. Věstník Ústředního Ústavu Geologického 58, 159–170.

Štorch, P., 1998a. Graptolites of the *Pribylograptus leptotheca* and *Lituigraptus convolutus* biozones of Tmaň (Silurian, Czech Republic). Journal of the Czech Geological Society 43, 209–272.

Štorch, P., 1998b. Biostratigraphy, palaeobiogeographical links and environmental interpretation of the Llandovery and Wenlock graptolite faunas of peri-Gondwanan Europe. In: Gutiérrez-Marco, J.C., Rábano, I. (Eds.). Proceedings 6th International Graptolite Conference (GWG-IPA) & 1998 Field Meeting, IUGS Subcommission on Silurian Stratigraphy. Temas Geológico-Mineros ITGE 23, 126–129.

Štorch, P., 2015. Graptolites from the Rhuddanian–Aeronian boundary interval (Silurian), Prague Synform, Czech Republic. Bulletin of Geosciences 90, 841–891.

Sung, S.H., 1941. Wenlock graptolites from Jenhochiao, Paoshan District, Yunnan. Bulletin of the Geological Society of China 21, 257–260.

Talent, J.A., Mawson, R., Simpson, A., 2003. Silurian of Australia and New Guinea: biostratigraphic correlations and paleogeography. New York State Museum Bulletin 493, 181–219.

Thein, M.L., 1973. The Lower Paleozoic stratigraphy of western part of the Southern Shan State, Burma. Bulletin of the Geological Society of Malaysia 6, 143–163.

Toghill, P., 1969. Discussion of the terms ‘Llandovery Series’ and ‘Valentian Series’ as time divisions of the Silurian. Proceedings of the Geological Society, London 1651, 235–238.

Torsvik, T.H., Cocks, L.R.M., 2009. The Lower Palaeozoic palaeogeographical evolution of the northeastern and eastern peri-Gondwanan margin from Turkey to New Zealand. In: Bassett, M.G. (Ed.), Early Palaeozoic peri-Gondwana terranes: new insights from tectonics and biogeography. Geological Society, London, Special Publication 325, 3–21.

Torsvik, T.H., Cocks, L.R.M., 2013a. Gondwana from top to base in space and time. Gondwana Research 24, 999–1030.

Torsvik, T.H., Cocks, L.R.M., 2013b. New global palaeogeographical reconstructions for the Early Palaeozoic and their generation. In: Harper, D.A.T., Servais, T. (Eds.), Early Palaeozoic Biogeography and Palaeogeography. Geological Society, London, Memoirs 38, 5–24.

Torsvik, T.H., Cocks, L.R.M., 2016. Earth history and palaeogeography. Cambridge University Press. 317 pp.

Whittington, H.B., 1954. Geological reconnaissance between Loilem and Ke-Hsi Mansam, Southern Shan States. Records of the Geological Survey of India 78, 203–216.

Williams, M., Zalasiewicz, J., Boukhamsin, H., Cesari, C., 2016. Early Silurian (Llandovery) graptolite assemblages of Saudi Arabia: biozonation, palaeoenvironmental significance and biogeography. Geological Quarterly 60, 1–23.

Wolfart, R., Win, U.M., Boiteau, S., Wai, U.M., Cung, U.P.U., Lwin, U.T., 1984. Stratigraphy of the Western Shan massif, Burma. Geologisches Jahrbuch 57, 1–92.

Zalasiewicz, J.A., Taylor, L., Rushton, A.W.A., Loydell, D.K., Rickards, R.B., Williams, M., 2009. Graptolites in British stratigraphy. Geological Magazine 146, 785–850.

Zhang, Y., Fan, J., Liu, X., 2009. Graptolite biostratigraphy of the Shihtien Formation (Darriwilian) in West Yunnan, China. Bulletin of Geosciences 84, 35–40.

Zhang, Y., Wang, Y., Zhan, R., Fan, J., Zhou, Z., Fang, X., 2014. Ordovician and Silurian stratigraphy and palaeontology of Yunnan, Southwest China. Science Press, Beijing. 138 pp.

Zhou, Z.Y., Zhen, Y. Y., 2008. Trilobite-constrained Ordovician biogeography of China with reference to the faunal connections with Australia. Proceedings of the Linnean Society of New South Wales 129, 183–195.

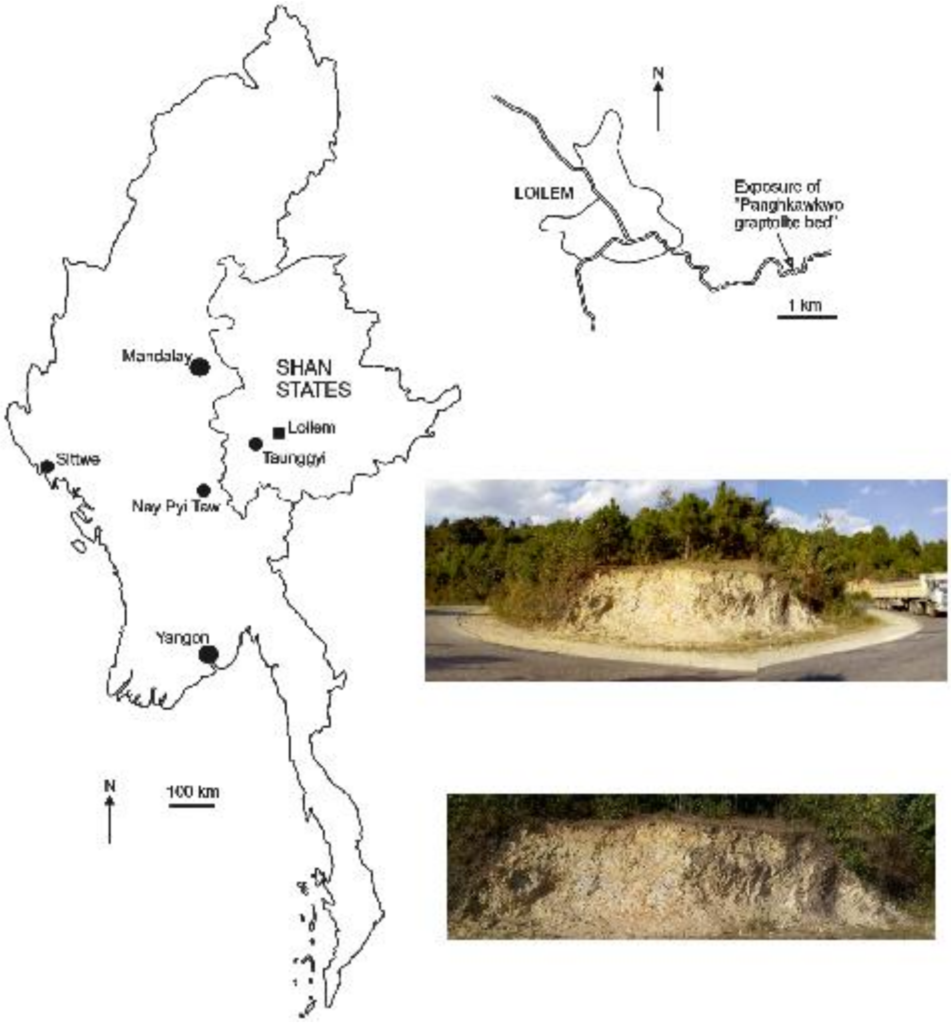

Fig. 1. Maps showing location of studied section and photographs of the exposure which has a stratigraphical thickness of 13.13 m.

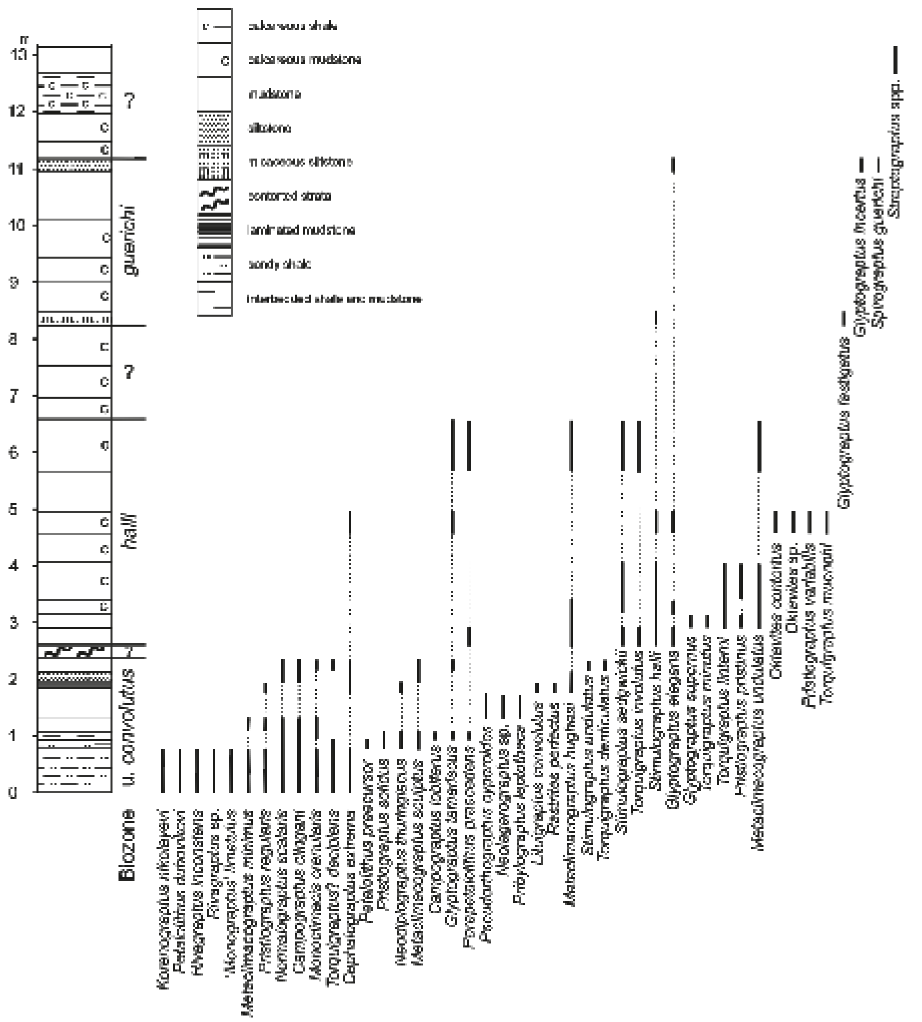

Fig. 2. Log and graptolite range chart for the studied section through the "Panghkawkwo graptolite bed".

Fig. 3. Graptolites from the Panghkawkwo logged section. A. *Cephalograptus extrema* Bouček and Přibyl, BGS FOR 6085, *halli* Biozone. B. *Korenograptus nikolayevi* (Obut), BGS FOR 6086, *convolutus* Biozone. C. *Metaclimacograptus undulatus* (Kurck), BGS FOR 6087, *halli* Biozone. D. *Neodiplograptus thuringiacus* (Kirste), BGS FOR 6088, *convolutus* Biozone. E. *Pristiograptus variabilis* (Perner), BGS FOR 6089, *halli* Biozone. F. *Normalograptus scalaris* (Hisinger), BGS FOR 6090, *convolutus* Biozone. G. *Metaclimacograptus hughesi* (Nicholson), BGS FOR 6091, *halli* Biozone. H, *Rivagraptus inconstans* Koren' and Rickards, BGS FOR 6092, *convolutus* Biozone. I, *Metaclimacograptus sculptus* (Chen and Lin), BGS FOR 6093, *convolutus* Biozone. J. *Pristiograptus solidus* Přibyl, BGS FOR 6094, *convolutus* Biozone. K. *Petalolithus dubovikovi* (Obut and Sobolevskaya), BGS FOR 6095, *convolutus* Biozone. L. *Metaclimacograptus minimus* (Paškevičius), BGS FOR 6096, *convolutus* Biozone. M. *Glyptograptus elegans* Packham, BGS FOR 6097, *halli* Biozone. N, *Parapetalolithus praecedens* (Bouček and Přibyl),

BGS FOR 6098, *halli* Biozone. O, *Glyptograptus fastigatus* Haberfelner, BGS FOR 6099, *guerichi* Biozone. P. *Glyptograptus incertus* Elles and Wood, BGS FOR 6100, *guerichi* Biozone. Q, *Spirograptus guerichi* Loydell, Štorch and Melchin, BGS FOR 6101, *guerichi* Biozone. Scale bar represents 2 mm.

Fig. 4. Graptolites from the Panghkawkwo logged section. A. *Pristiograptus pristinus* Přibyl, BGS FOR 6102, *halli* Biozone. B. *Oktavites* sp., BGS FOR 6103, *halli* Biozone. C. *Torquigraptus denticulatus* (Törnquist), BGS FOR 6104, *convolutus* Biozone. D. *Torquigraptus muenchi* (Přibyl), BGS FOR 6105, *halli* Biozone. E. *Torquigraptus linterni* Williams et al., BGS FOR 6106, *halli* Biozone. F. '*Monograptus*' *limatulus* Törnquist, BGS FOR 6107, *convolutus* Biozone. G. *Oktavites contortus* (Perner), BGS FOR 6108, *halli* Biozone. H. *Pribylograptus leptotheca* (Lapworth), BGS FOR 6109, *convolutus* Biozone. I. *Lituigraptus convolutus* (Hisinger), BGS FOR 6110, *convolutus* Biozone. J. *Torquigraptus*? *decipiens* (Törnquist), BGS FOR 6111, *convolutus* Biozone. K. *Glyptograptus supernus* Fu, BGS FOR 6112, *halli* Biozone. L. *Petalolithus praecursor* Bouček and Přibyl, BGS FOR 6113, *convolutus* Biozone. M. *Torquigraptus minutus* (Chen), BGS FOR 6114, *halli* Biozone. N. *Rastrites perfectus* Přibyl, BGS FOR

6115, *convolutus* Biozone. O. *Monoclimacis crenularis* (Lapworth), BGS FOR 6116, *convolutus* Biozone. Scale bar represents 2 mm.

Fig. 5. Graptolites from the Panghkawkwo logged section (biozone indicated) and ex situ specimens. A. *Rivagraptus* sp., BGS FOR 6117, *convolutus* Biozone. B. *Campograptus clingani* (Carruthers), BGS FOR 6118, *convolutus* Biozone. C, *Glyptograptus* sp. 1, BGS FOR 6119. D, *Stimulograptus undulatus*, BGS FOR 6120, *convolutus* Biozone. E, H. *Neolagarograptus* sp., BGS FOR 6121, 6124, *convolutus* Biozone. F. *Pristiograptus regularis* (Törnquist), BGS FOR 6122, *convolutus* Biozone. G. *Glyptograptus tamariscus* (Nicholson), BGS FOR 6123. I. '*Monograptus*' *mirus* Perner, BGS FOR 6125. J. *Stimulograptus sedgwickii* (Portlock), BGS FOR 6126, *halli* Biozone. K. *Stimulograptus halli* (Barrande), BGS FOR 6127, *halli* Biozone. L. *Torquigraptus*? *decipiens* (Törnquist), BGS FOR 6128. M.

Glyptograptus sp. 2, BGS FOR 6129. N. *Metaclimacograptus* sp. *sensu* Loydell and Maletz (2009), BGS FOR 6130. O. *Normalograptus* cf. *angustus* (Perner), BGS FOR 6131. Scale bar represents 2 mm.

Fig. 6. Ex situ graptolites from Panghkawkwo. A. *Rickardsograptus sinuatus* (Nicholson), BGS FOR 6132. B. *Glyptograptus enodis* Packham, BGS FOR 6133. C. *Normalograptus rectangularis* (M^{c}Coy), BGS FOR 6134. D. *Neodiplograptus* sp., BGS FOR 6135. E. *Metaclimacograptus slalom* Zalasiewicz, BGS FOR 6136. F. *Rivagraptus cyperoides* (Törnquist), BGS FOR 6137. G. *Pernerograptus sudburiae* (Hutt), BGS FOR 6138. H. *Neodiplograptus thuringiacus* (Kirste), BGS FOR 6139. I. *Neodiplograptus elongatus* (Churkin and Carter), BGS FOR 6140. J. *Neodiplograptus magnus* (H. Lapworth), BGS FOR 6141. K. *Pristiograptus concinnus* (Lapworth), BGS FOR 6142. Scale bar represents 2 mm.

Fig. 7. Ex situ graptolites from Panghkawkwo. A. *Metaclimacograptus undulatus* (Kurck), BGS FOR 6143. B. *Pseudorthograptus* cf. *physophora sensu* Štorch (2015), BGS FOR 6144. C. *Petalolithus* sp., BGS FOR 6145. D. *Agetograptus malayensis* (Jones), BGS FOR 6146. E. *Metaclimacograptus hubeiensis* (NIGP), BGS FOR 6147. F. *Glyptograptus burtoni* Jones, BGS FOR 6148. G. *Pseudorthograptus insectiformis* (Nicholson), BGS FOR 6149. H. *Petalolithus ovatoelongatus* (Kurck), BGS FOR 6150. I. *Glyptograptus perneri* Štorch, BGS FOR 6151. J. *Glyptograptus serratus* Elles and Wood, BGS FOR 6152. K. *Rivagraptus bellulus* (Törnquist), BGS FOR 6153. L. *Pseudorthograptus obuti* (Rickards and Koren'), BGS FOR 6154. M. *Lituigraptus*? sp. 1, BGS FOR 6155. N. *Neodiplograptus magnus* (H. Lapworth), BGS FOR 6156. O. *Monoclimacis imago* (Zalasiewicz), BGS FOR 6157. Scale bar represents 2 mm.

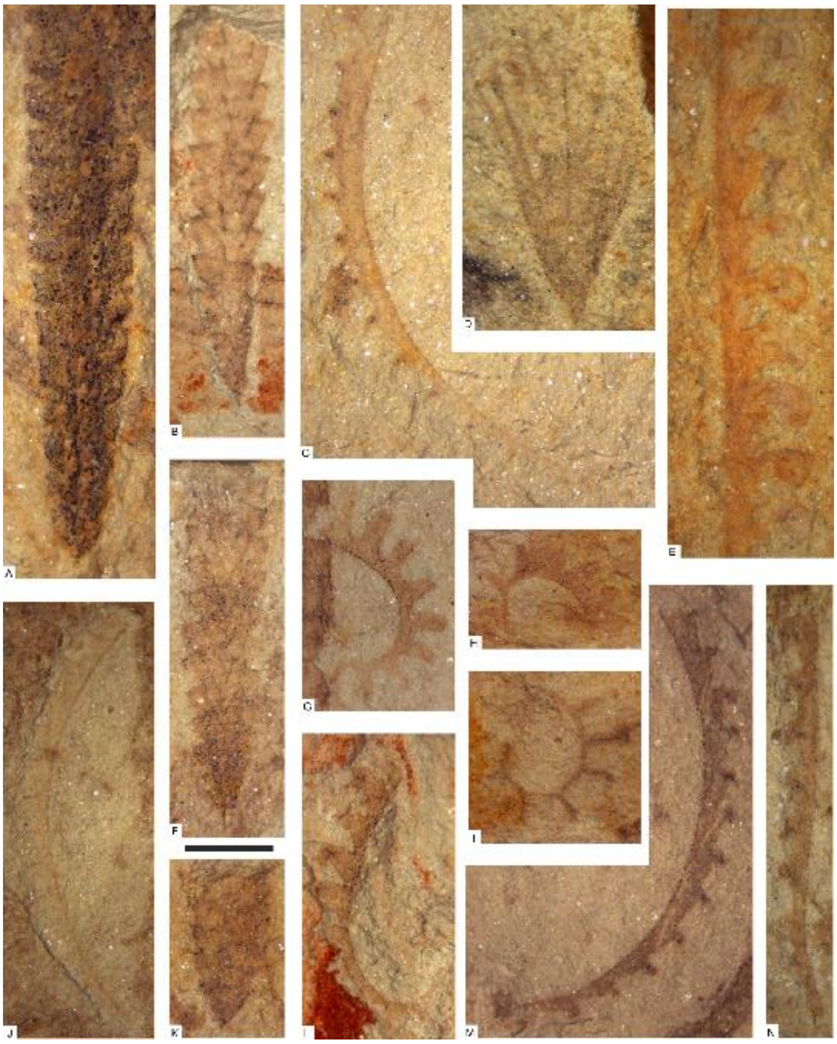

Fig. 8. Ex situ graptolites from Panghkawkwo. A. *Pseudoglyptograptus* sp. BGS FOR 6158. B. *Agetograptus secundus* Obut and Sobolevskaya, BGS FOR 6159. C. *Pernerograptus bicornis* (Hutt), BGS FOR 6160. D. *Petalolithus folium* (Hisinger), BGS FOR 6161. E, N. *Campograptus lobiferus* (M[c]Coy), BGS FOR 6162, 6171. F. *Agetograptus primus* Obut and Sobolevskaya, BGS FOR 6163. G. *Demirastrites pectinatus* (Richter), BGS FOR 6164. H. *Demirastrites similis* (Elles and Wood), BGS FOR 6165. I. *Lituigraptus richteri* (Perner), BGS FOR 6166. J. *Coronograptus gregarius* (Lapworth), BGS FOR 6167. K. *Rivagraptus sentus* Koren' and Rickards, BGS FOR 6168. L. *Torquigraptus denticulatus* (Törnquist), BGS FOR 6169. M. *Pernerograptus difformis* (Törnquist), BGS FOR 6170. Scale bar represents 2 mm.

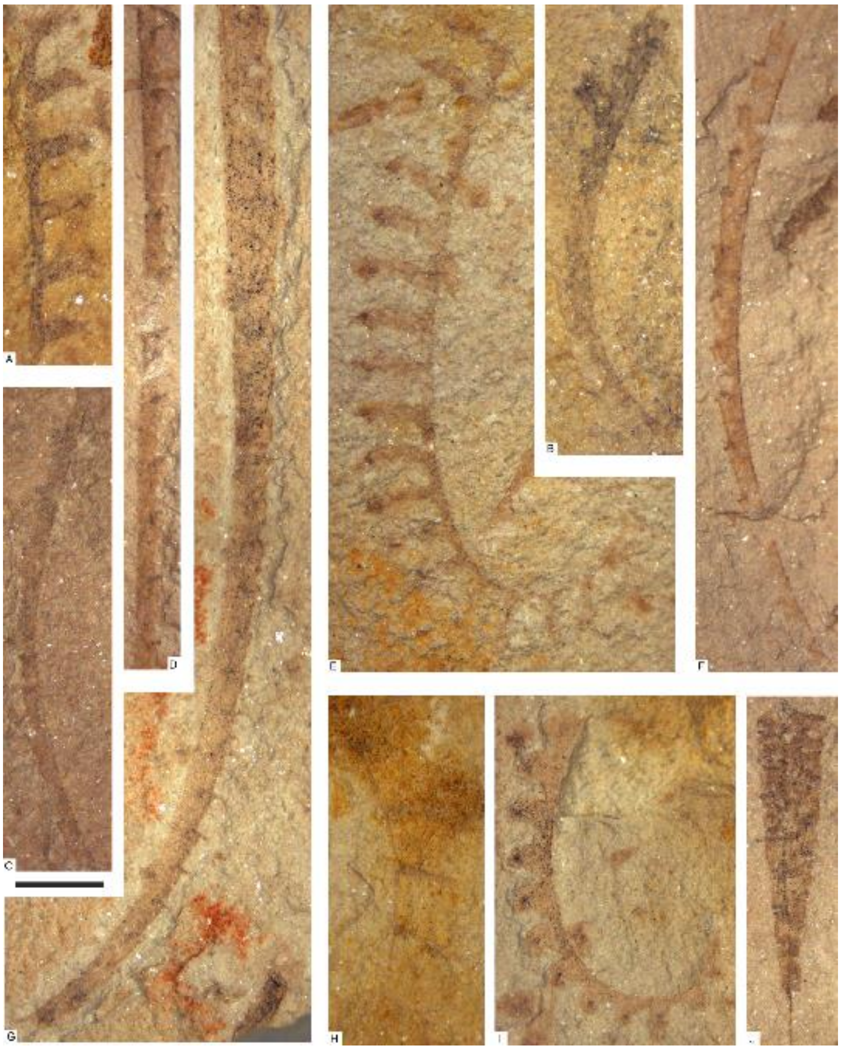

Fig. 9. Ex situ graptolites from Panghkawkwo. A. *Lituigraptus*? sp. 2, BGS FOR 6172. B. '*Monograptus*' *havliceki* Štorch, BGS FOR 6173. C. *Neolagarograptus helenae* (Štorch), BGS FOR 6174. D. *Neolagarograptus impolitus* Štorch, BGS FOR 6175. E. *Demirastrites triangulatus* (Harkness), BGS FOR 6176. F. *Pernerograptus austerus* (Törnquist) *sensu lato*, BGS FOR 6177. G. *Pernerograptus sequens* (Hutt) or *Per. praecursor* (Elles and Wood), BGS FOR 6178. H. *Rastrites* cf. *erectus sensu* Štorch (1998), BGS FOR 6179. I. *Campograptus millepeda* (M^c^Coy) BGS FOR 6180. J. *Rhaphidograptus toernquisti* (Elles and Wood), BGS FOR 6181. Scale bar represents 2 mm.

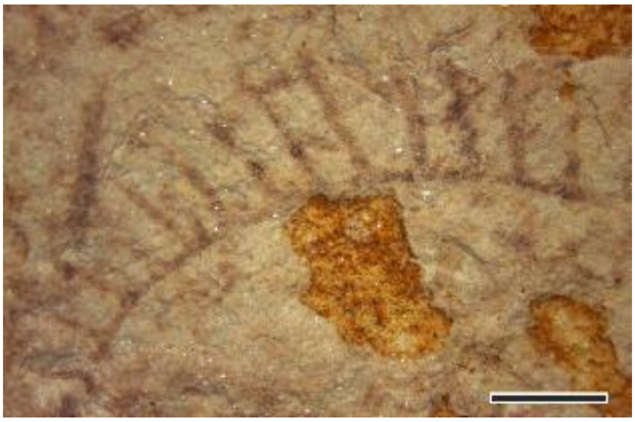

Fig. 10. Ex situ graptolite from Panghkawkwo. *Rastrites longispinus* Perner, BGS FOR 6182. Scale bar represents 2 mm.